The Role of Carbon Capture and Sequestration Policies for Climate Change Mitigation

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Abstract

This paper takes the 'policy failure' in establishing a global carbon price for efficient emissions reduction as a starting point and analyzes to what extent technology policies can be a reasonable second-best approach. From a supply-side perspective, carbon capture and storage (CCS) policies differ substantially from renewable energy policies: they increase fossil resource demand and simultaneously lower emissions. We analyze CCS and renewable energy policies in a numerical dynamic general equilibrium model for settings of imperfect or missing carbon prices. We find that in contrast to renewable energy policies, CCS policies are not always capable of reducing emissions in the long run. If feasible, CCS policies can carry lower social costs compared to renewable energy policies, in particular when second-best policies are only employed temporally. In case fossil resources are abundant and renewable energy costs low, renewable energy policies perform better. Our results indicate that a pure CCS policy or a pure renewable energy policy carry their own specific risks of missing the environmental target. A smart combination of both, however, can be a robust and low-cost temporary second-best policy.

Keywords: renewable energy policy, supply-side dynamics, carbon pricing, global warming, CCS, Hotelling, second-best

1. Introduction

While a global carbon price is the economist's textbook advice for reducing emissions efficiently, governments struggle with the introduction of substantial domestic or even global carbon prices. Until now, states have not been able to agree neither on a global emissions trading scheme, nor on a globally harmonized carbon tax. The reasons are numerous: Besides free-rider incentives, carbon pricing policies re-distribute disposable income, rents and wealth through several channels on a domestic as well as a global scale (Fullerton, 2011). These redistributions can be regressive, e.g. increased energy prices due to cleaner energy provision reduce the disposable income of low-income households more than for high-income households (e.g. Parry, 2004; Parry and Williams III, 2010). However, climate

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policy can also have a progressive effect if revenues from carbon pricing are transferred to low-income households.

In any case, the transformation of income and rents creates a bargaining and rent-seeking process about compensation schemes that impedes the implementation of efficient policies: Internationally, negotiating explicit transfers between countries is a difficult task. Every party insists on an advantageous burden sharing rule and fears to be hoodwinked regarding the sharing of costs and benefits. Domestically, compensation policies for higher energy prices may imply high transaction costs, in particular in developing countries which often tend to have insufficient public institutions.

Despite the difficulties to establish effective carbon prices, many governments euphorically promote renewable energy by targeted technology policies. At least 118 countries established explicit renewable energy targets or policies (REN21, 2011). Global investments into new renewable energy capacities are higher than into fossil energy capacities in the electricity sector (IPCC, 2011, Ch. 11, p. 878). Public support for these measures is high because renewable energy is associated with several local and national benefits, ranging from improved air quality over technological first-mover advantages to greater energy security and higher energy access in remote rural areas (IPCC, 2011, Ch. 11.3).[2]

In this paper, we investigate the welfare costs of a missing price on carbon (incomplete or delayed pricing), and implications of technology policies as second-best alternatives.[3] Are technology policies a reasonable alternative to carbon prices for short or even longer time periods? And if so, which technologies (renewable energy or CCS) should be promoted by governments? How do renewable energy and CCS promoting policies differ regarding welfare, energy costs, rents, public revenues and environmental risks? We provide an extensive discussion for the specific case of renewable energy policies in Kalkuhl et al. (2013): Despite the political appeal, a naive up-scaling of renewable energy deployment is very costly and the resulting emissions are highly sensitive to the level of subsidies which undermines environmental effectiveness. This study adds technology policies for carbon capture and sequestration (CCS) as well as portfolios of technology policies.

The underlying supply-side argument by Sinn (2008) provides the basis for our analysis of CCS policies: Policies reducing the demand for fossil resources can – if ill-designed – accelerate resource extraction and thus emissions. This issue has been discussed for suboptimal carbon taxes as well as suboptimal renewable energy subsidies (Sinn, 2008; Grafton et al., 2010; Hoel, 2010; Edenhofer and Kalkuhl, 2011; Gerlagh, 2011). In addition to intertemporal re-allocation of carbon extraction, unilateral carbon pricing policies can induce supply-side leakage via reduced (global) fossil resource prices (Eichner and Pethig, 2011). CCS differs from other mitigation options (in our framework: energy efficiency increases, renewable energy use) as it allows using fossil resources with low atmospheric emissions. Hence, promoting CCS could increase fossil resource demand and simultaneously reduce carbon emissions. Therefore, we concentrate on the role of CCS policies and their difference to renewable energy policies – in particular regarding the supply-side dynamics of fossil resources.

So far, there has been only little research that focuses on the second-best aspect of CCS policies. A number of theoretical papers address the efficient use of CCS under several geological and eco-

[2] This corresponds to the suggestion of Victor (2011) that support for policies is greatest if costs are widely spread or hidden and benefits are concentrated and explicit. By contrast, the benefits of carbon pricing are far more spread out (in fact, across the globe and into the future) and can involve costs that are concentrated on a few sectors and companies that are well-organized.

[3] We use the term second-best as follows: An optimal second-best policy is a policy that maximizes social welfare given that the policy space is constrained.

nomic conditions (Amigues et al., 2010; Coulomb and Henriet, 2010; Le Kama et al., 2011). Several numerical models have estimated the role of CCS for reducing mitigation costs (e.g. van der Zwaan and Gerlagh, 2009). However, only few papers provide an explicit analysis of policy instruments. Fischer and Salant (2010) find within a Hotelling model framework that mal-adjusted carbon taxes, renewable energy subsidies or energy efficiency improvements can be ineffective or even accelerate extraction and emissions. An obligatory mandate to capture and sequester a certain share of emissions, however, does always reduce emissions and is thus the most robust policy. Hoel and Jensen (2010) show in a two-period Hotelling model that reducing the long-term costs for renewable energy can lead to higher emissions while reducing the long-term costs for CCS always reduces emissions.

For this analysis, we extend the intertemporal general equilibrium model described in Kalkuhl et al. (2012a) by a CCS technology to study the performance of CCS policies in a second-best setting where carbon prices are restricted. To integrate the supply-side dynamics of fossil resource extraction, a general equilibrium model on a global scale is necessary. Although there is no global real-world government that could implement carbon pricing or technology policies, our model results give an important (least-cost) estimation about the performance of several policies instruments. The model presented in Sec. 2 is in spirit to the DEMETER model (Gerlagh et al., 2004; Gerlagh and van der Zwaan, 2004) or the top-down energy-economic model developed by Grimaud et al. (2011): Optimal policies are calculated subject to an intertemporal market equilibrium. As DEMETER does not contain an intertemporal fossil resource sector, it cannot capture the supply-side dynamics of fossil fuels. Within a second-best policy analysis in DEMETER, Gerlagh and van der Zwaan (2006) explore the role of renewable energy subsidies and a portfolio standard for CCS for climate change mitigation when innovation spillovers exist. In contrast to DEMETER, the model of Grimaud et al. (2011) contains an intertemporally optimizing fossil resource sector. While Grimaud et al. (2011) focus on carbon pricing and R&D subsidies, no policy analysis is conducted with respect to explicit technology deployment policies under carbon-pricing constraints.

In our general equilibrium model, we consider several second-best settings with respect to the carbon price (Section 3). In Section 3.1, the implemented carbon price is lower than the carbon price necessary to achieve a certain mitigation target and governments can use low-carbon technology policies to further reduce emissions. This corresponds to a world where governments want to reduce emissions but are reluctant to introduce carbon prices at the efficient level. Instead, they aim to reduce emissions by promoting low-carbon technologies in form of renewable energy or CCS. Section 3.2 assumes that the international community is not able to establish a global carbon price in the near future. Governments and firms expect that a carbon price will eventually be introduced in the future and governments use technology policies for bridging the gap. We consider the public revenue requirements of second-best policies in Section 3.3 as they might be important for the practical feasibility.

We then perform a sensitivity analysis with respect to crucial parameters (Section 4.1) and deviations from optimal second-best policies (Section 4.2). The latter suggests how sensitively carbon emissions respond to suboptimally chosen policies. Finally, we sum up our main findings and conclude with some further considerations about the design of technology policies for mitigation (Section 5).

2. Numerical model: Analysis in an intertemporal general equilibrium model

Under highly stylized conditions, it is possible to show that a pure CCS subsidy can be an efficient alternative to carbon pricing. In Kalkuhl et al. (2012b), we show this in a reduced partial equilibrium model for the restrictive assumptions of large storage capacities and no leakage from storage sites. This section presents a numerical general equilibrium model that allows us to relax these restrictive assumptions and address our research questions in a more realistic setting. In particular, we will allow for positive leakage rates, imperfect carbon capture, imperfect substitutability between energy technologies, and abundance of fossil resources – all of which greatly complicate an analytical treatment.

The intertemporal general equilibrium model contains a generic top-down representation of different power generation technologies. Its formulation as non-linear program and its implementation in GAMS (General Algebra Modeling System, Brooke et al., 2005) allows calculating welfare maximizing policies subject to environmental constraints (i.e. a mitigation target) or political constraints (i.e. restriction on carbon prices).

For the following numerical analysis we extend the model described in Kalkuhl et al. (2012a) by an additional fossil energy sector that sequesters emissions from fossil fuel combustion, and a storage sector that transports and stores carbon underground. We model the government as Stackelberg leader who anticipates the reaction of the market economy on its policies. With this top-level optimization of the government, the welfare-maximizing potential of a variety of policy instruments ranging from carbon taxes to subsidies for renewable energy and CCS are studied.

2.1. The technological structure

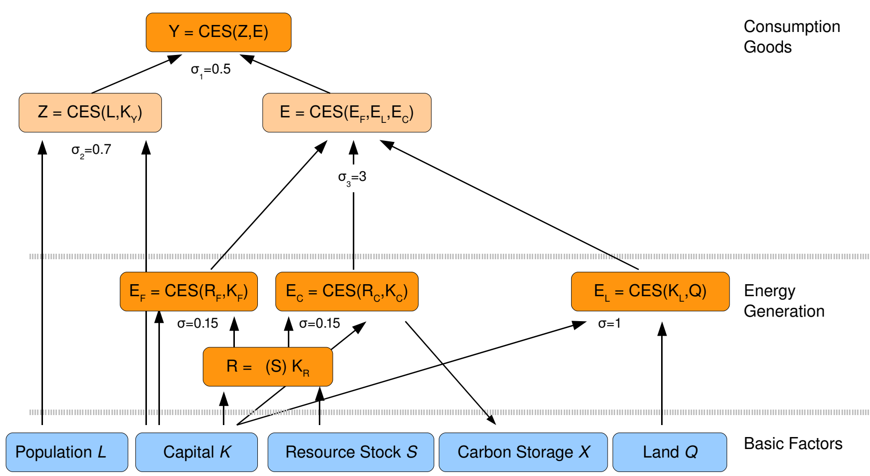

Figure 1: Production technology.

The basic model equations are presented in Kalkuhl et al. (2012a); here, we restrict the explanation to a general description of the economic sectors and focus in more detail on the sectors affected by CCS. If not stated otherwise, the first-order conditions can be found in Kalkuhl et al. (2012a).

Final output sector

Fig. 1 gives an overview of the technological structure of the economy. Economic output Y is generated by energy E and a composite Z of capital K_Y and labor L. Electric energy is composed of conventional fossil energy E_F causing carbon emissions, carbon-neutral renewable energy E_L, which exhibits learning-by-doing effects, and a CCS fossil energy technology E_C which sequesters carbon emissions. The constant-elasticity-to-scale (CES) production technology is described by:

$$Y(Z,E) = \left(a_1 Z^{\frac{\sigma_1-1}{\sigma_1}} + (1-a_1)E^{\frac{\sigma_1-1}{\sigma_1}}\right)^{\frac{\sigma_1}{\sigma_1-1}} \tag{1}$$

$$Z(K_Y,L) = \left(a_2 K_Y^{\frac{\sigma_2-1}{\sigma_2}} + (1-a_2)(A_Y L)^{\frac{\sigma_2-1}{\sigma_2}}\right)^{\frac{\sigma_2}{\sigma_2-1}} \tag{2}$$

$$E(E_F,E_L,E_C) = \left(a_3 E_F^{\frac{\sigma_3-1}{\sigma_3}} + b_3 E_L^{\frac{\sigma_3-1}{\sigma_3}} + c_3 E_C^{\frac{\sigma_3-1}{\sigma_3}}\right)^{\frac{\sigma_3}{\sigma_3-1}} \tag{3}$$

where σ are the respective elasticities of substitution, a_1,a_2,a_3,b_3,c_3 are share parameters and A_Y is an exogenously growing labor productivity factor. Population L likewise grows exogenously. Due to the high aggregation level we do not distinguish between different technologies within one of the three generic energy types. We also abstract from non-electric energy (in particular, transportation and heating) which would require a more differentiated CES nest.[4]

Firms in the production sector sell output, pay wages w for labor input, interest rates r for capital input and energy prices p_F, p_C, p_L for conventional fossil, CCS fossil and renewable energy, respectively. Additionally, subsidies for renewable energy τ_L and CCS fossil energy τ_C can be imposed by the government. By differentiating the profit function $\pi_Y = Y(K_Y, L, E_F, E_L, E_C) - rK_Y - p_F E_F - (p_L - \tau_L)E_L - (p_C - \tau_C)E_C$ with respect to inputs, we obtain the usual first-order conditions.

Conventional fossil energy sector

The conventional fossil energy sector uses capital K_F and fossil resources R_F for generating energy at the productivity level A_F according to:

$$E_F(K_F,R_F) = A_F\left(a_F K_F^{\frac{\sigma-1}{\sigma}} + (1-a_F)R_F^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{4}$$

Firms sell energy at the price p_F, rent capital at the interest rate r and purchase fossil resources at the price p_R. Additionally, the government may levy a carbon tax τ_R for fossil resources R_F that are cause carbon emissions when burnt. The profit function reads $\pi_F = p_F E_F(K_F, R) - rK_F - (p_R + \tau_R)R_F$.

CCS fossil energy sector

The basic fossil energy production technology (4) remains unchanged when capturing of carbon emissions for sequestration is added. However, due to the energy penalty and the need to install additional equipment (capital costs), productivity $A_C \leq 1$ is lowered and the relative factor inputs may change due to a_C:

$$E_C(K_C,R_C) = A_C\left(a_C K_C^{\frac{\sigma-1}{\sigma}} + (1-a_C)R_C^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{5}$$

In contrast to the conventional fossil energy sector, the CCS energy sector has to pay the transportation and storage price p_X per unit of captured carbon R_X. Depending on the capture technology, a fixed

[4]There is an important trade-off between technological resolution and numerical feasibility within our model framework: Integration of further technologies makes it more likely that corner solutions occur, i.e. that one technology is not used in the market equilibrium. This, however, is incompatible with the non-linear optimization solver who requires a continuously differentiable set of constraints.

share $\theta \leq 1$ of carbon emissions is captured, i.e. $R_X = \theta R_C$. Thus, a carbon tax on non-captured emissions $(1-\theta)R_C$ applies. For the corresponding profit function $\pi_C = p_C E_C(K_C, R_C) - rK_C - p_R R_C - p_X \theta R_C - \tau_{R,t}(1-\theta)R_C$ the usual static first-order conditions result.

Fossil resource sector

Fossil resources $R = R_F + R_C$ that are used in both fossil energy sectors are extracted from a finite resource stock S with capital input K_R according to $R(S, K_R) = \kappa(S)K_R$. With ongoing depletion of S, more capital is needed to extract one unit of resources. We use a typical extraction cost curve (Rogner, 1997; Nordhaus and Boyer, 2000) to describe the decrease of capital productivity $\kappa(S)$, implying increasing extraction costs $\kappa(S) = \chi_1 / \left(\chi_1 + \chi_2 \left(\frac{S_0 - S}{S_0}\right)^{\chi_3}\right)$. The profit function in the extraction sector reads $\pi_R = p_R R(S, K_R) - rK_R$ where additionally the depletion dynamics $S_{t+1} = S_t - R_t$ have to be considered.

Sequestration sector

The sequestration sector transports captured carbon R_X from the plant and stores it underground in storage X. As storage is limited, storage becomes essentially an exhaustible resource. Leakage R_L at the rate $\delta_X \geq 0$, however, increases the storage capacity and is taxed with the carbon price τ_R.[5] Similar to the fossil resource sector, storage costs $h(X)$ depend on the size of the remaining storage and decrease in X: Easily accessible storage sites are used first while sites with difficult access and monitoring or located at a a long distance from the plant are used later. With the instantaneous profit function $\pi_X = (p_X - h(X))R_X - \tau_R R_L$, the intertemporal optimization problem reads:

$$\max_{R_{X,t}} \sum_{t=0}^{T} \pi_{X,t} \Pi_{s=0}^{t} \left[1 + (r_s - \delta)\right]^{-1}$$

subject to:

$$X_{t+1} = X_t - (R_{X,t} - R_{L,t}), \qquad X_t \geq 0, \qquad X_0 \text{ given} \tag{6}$$

$$R_{L,t} = \delta_X (X_0 - X_t) \tag{7}$$

$$h(X_t) = c_1 + c_2 \left(\frac{X_0 - X_t}{X_0}\right)^{c_3} \tag{8}$$

where X_0 is the (initial) size of the storage and δ denotes the capital depreciation rate which is subtracted from the marginal rate of capital productivity r to obtain the net discount rate. The first-order conditions are stated in AppendixA.

Renewable energy sector

Renewable energy is generated from capital K_L and land Q: Its generation costs decrease in cumulative output H. This learning-by-doing effect is modeled as a productivity increase $A_L(H)$, which is perfectly anticipated by the market economy (e.g. as if innovation spillovers were already internalized through a technology policy).[6]

[5] We consider the simplifying case of exponential leakage. A possible alternative is found in van der Zwaan and Gerlagh (2009), who develop a two-layer leakage model where leakage rates are non-constant.

[6] In Kalkuhl et al. (2012a) we analyze how spillovers or risk-premiums can lead to costly lock-ins into intertemporally inefficient low-carbon technologies. In order to concentrate on the efficiency cost of second-best policies for imperfect carbon pricing, we abstract from these additional market failures in the renewable energy sector.

By selling renewable energy at price p_L and renting capital at the interest rate r, the instantaneous profit function reads $\pi_L = p_L E_L(A_L(H), K_L, Q) - rK_L$. The production technology is Cobb-Douglas $E_L(A_L, K_L, Q) = A_L K_L^{\nu} Q^{\nu-1}$ with the productivity level $A_L = \frac{A_{L,max}}{1+\left(\frac{\Omega}{H}\right)^{\gamma}}$ and Q being a fixed-factor component (land or space) which implies decreasing returns to scale in capital. Cumulative capacity $H_{t+1} = H_t + (E_{L,t} - E_{L,t-1})$ is a proxy for experience (that increases productivity). $A_{L,max}$ and Ω are scaling factors and γ is the learning exponent.

Household sector

The representative household maximizes intertemporal utilitarian social welfare $\sum_{t=0}^{T}(1+\rho)^{-t} L_t U(C_t/L_t)$ with the discount rate ρ and the CES-utility function in per-capita consumption $U(C/L) = (C/L)^{1-\eta}/(1-\eta)$. The household receives wages, capital income, the firms' profits $\pi = \sum_j \pi_j$ and (positive or negative) lump-sum government transfers Γ. It invests I in the aggregate capital stock $K = \sum K_j$. Thus, consumption is $C = wL + rK + \pi + \Gamma - I$ and the capital stock evolves at $K_{t+1} = (1-\delta)K_t + I_t$ with the depreciation rate δ. The government balances tax incomes and subsidy expenditures with the household's lump-sum tax according to $\Gamma = \tau_R(R_F + (1-\theta)R_C + R_L) - \tau_L E_L - \tau_C E_C$.

2.2. *Atmospheric carbon emissions and the carbon budget*

Emissions occur at several points in the economy: Conventional fossil energy firms emit R_F; in the CCS fossil energy sector the non-captured share of fossil resources $(1-\theta)R_C$ is released into the atmosphere; and carbon R_L leaks from the CCS storage. Total emissions amount to $Em = R_F + (1-\theta)R_C + R_L$. The government's mitigation target is formulated as a cumulative constraint on emissions with $B_{t+1} = B_t - Em_t$ where $B_t \geq 0$ and $B(0) = B_0$ is the size of the carbon budget.

2.3. *Implementation and policy assessment*

We consider three types of equilibria: (i) the *social planner optimum* is obtained by maximizing the households utility subject to the technological constraints; (ii) the *laissez-faire market equilibrium* is defined as the solution of the system of equations describing technology, profits, budgets and the first-order conditions where all policies are set to zero (i.e. $\tau_R = \tau_L = \tau_C = 0$); (iii) the *optimal policy market equilibrium* is calculated from (ii) by additionally maximizing the household's utility over the policy variables (τ_R, τ_L, τ_C).

Without a mitigation target (i.e. if $B_0 \geq S_0$) the laissez-faire economy equals the social optimum because there are no further market failures in the economy. Since no emissions are reduced, we also denote this case as the *business-as-usual* (BAU) scenario. When the mitigation target is considered and the government can use all policy instruments without restrictions, the optimal policy market equilibrium equals the social optimum.[7]

We will focus on optimal second-best policies for fossil-CCS and renewable energy when the carbon tax variable τ_R is constrained. τ_L and τ_C are calculated to achieve the carbon budget at least costs. We evaluate the policies with respect to the laissez-faire (BAU) economy (without mitigation) and the social planner optimum under a mitigation target. Policies are evaluated according to their welfare change measured in balanced-growth equivalences (BGE) (Mirrlees and Stern, 1972).

[7]In this paper, there are no additional market failures beyond the mitigation target. Therefore, it is sufficient for the government to choose τ_R appropriately. No additional technology policies are needed.

2.4. Calibration of the model

The parameters for the economy without CCS are based on Kalkuhl et al. (2012a). They are slightly adjusted as in this study the energy sector encompasses only electricity. Thus, the share of energy expenditures out of total income is lower (3 percent) and less emissions occur in the BAU scenario. The extraction cost curve of fossil resources is further set to emulate the extraction cost dynamics of coal, as coal is the largest energy source used for electricity generation. Due to the large uncertainty in available resources and costs, we discuss extraction cost curves separately within the sensitivity analysis in Section 4.1. We employ a mitigation target by limiting cumulative emissions to 150 GtC – this corresponds to the cumulative emissions from the electricity sector for a two-degree temperature limit in Luderer et al. (2012).

For the CCS technology added in this study we reproduce typical estimations of costs and factor inputs available for CCS: IPCC (2005, Tab. TS.3) estimates 11–40% higher energy use to generate electricity under the CCS technology. If we set the share and productivity parameter to $a_C = 0.95$ and $A_C = 2.2$, respectively, we obtain a 20% higher fossil resource input for one unit of energy compared to non-captured fossil energy ("energy penalty") and costs for fossil energy with carbon capture increase by roughly 2 ct/kWh. This lies in the range of the IPCC (2005, Tab. TS.3) estimation of a 1.2–3.4 ct/kWh cost increase. We set $\theta = 0.95$ in our basic parametrization in line with the current ability of technologies to capture 80–99% of the emissions (IEA, 2010, Tab. 10.2).

There is uncertainty regarding the costs of carbon storage and transportation. In IPCC (2005, p. 260), costs for storage in depleted oil and gas fields as well as in saline formations range between 1 and 111 \$/tC. IEA (2010, p. 184) estimates transportation costs of 7–22 \$/tC per 100 km pipeline, IPCC (2005, p. 42) only 1–12 \$/tC per 100 km pipeline or shipping. We parametrize the CCS cost curve (Eq. 8) such that initial transportation and storage costs are 50 \$/tC; they increase to 65 \$/tC in 2100 when 710 GtC are stored in the social planner optimum. IPCC (2005, p. 197) estimates the size of geological storage in oil and gas fields between 184 GtC and 245 GtC, in unminable coal seams between 1 and 55 GtC, and in deep saline formations between 273 and 2,730 GtC.[8] In our basic parametrization, we choose a very large storage capacity of 3,500 GtC in order to avoid a hard constraint for CCS. Costs increase sharply if X approaches zero. With optimal carbon pricing, 290 GtC are stored underground, and in most of our model runs stored carbon does not exceed 1,000 GtC in 2100. Within geological formations IPCC (2005) finds it very likely that ≥ 99% of stored carbon remains underground within 100 years (i.e. $\delta_X \leq 10^{-4}$) and likely that ≥ 99% remains underground within 1,000 years (i.e. $\delta_X \leq 10^{-5}$). We assume a leakage rate of 0.01%. In the sensitivity analysis we vary this value as well as the storage capacity and the capture rate.

3. CCS policies if carbon pricing is imperfect

In the following we analyze the performance of second-best technology policies for CCS and renewable energy if carbon prices are imperfect. The basic idea of using second-best technology policies is to increase the relative price of emission-intensive technologies compared to low-carbon technologies. While carbon pricing provides a direct measure for this objective, subsidizing low-carbon

[8]Besides geological storage, there is also the possibility to store carbon in the oceans or in solid carbonates after accelerated mineral carbonation. The storage capacity of the oceans is practically unlimited. However, there are high uncertainties about the impacts for marine ecosystems and the permanency of storage. Mineral carbonation offers also a practically infinity large sink. However, both costs and land consumption from mining and disposal are high (IPCC, 2005, Ch. 6–7).

technologies has an indirect effect on the relative price between low-carbon and carbon-intensive technologies: if energy from low-carbon technology becomes sufficiently cheap through subsidies, energy consumers will switch to the latter and, hence, cause less emissions.

In the first subsection, we consider the case when carbon prices are too low to achieve the mitigation target. This is motivated by the observation that international or domestic compensation for the distributional effects of high carbon taxes is difficult to implement. The international community therefore may only agree on suboptimally low harmonized carbon taxes and a financing mechanism for additional technology policies. In the second subsection, we assume that the introduction of carbon prices is delayed substantially because no agreement can be achieved in the near future. Once scientific knowledge or social perception about climate damages changes, first impacts of global warming become visible or global coordination between nation states has been improved, the optimal tax can be implemented in the future. We therefore analyze how far technology policies can substitute temporarily missing carbon prices. Although our main focus lies on CCS subsidies, we will also discuss their performance relative to renewable energy subsidies as they are a popular second-best policy option.

3.1. Second-best policies for suboptimally low carbon prices

In our first analysis, we calculate optimal second-best policies if carbon taxes τ_R are set to a fixed fraction $0\% \leq \vartheta < 100\%$ of the socially optimal carbon tax τ_R^*. This tax is obtained from the shadow price of the social planner optimum or directly from the optimal policy market equilibrium when τ_R is unconstrained. The optimal carbon tax τ_R^* limits cumulative emissions efficiently to the carbon budget constraint. Subsidies on CCS or renewable energy are not needed in this case. However, if a suboptimal tax $\tau_R = \vartheta\tau_R^*$ is implemented, the carbon budget is violated – unless further instruments are used to reduce emissions. For this case, we consider three second-best policies:

`CCS` a pure CCS technology policy τ_C that limits emissions by subsidizing CCS; renewable energy subsidies τ_L are set to zero. Thus, the policy space is constrained to $\{\tau_R = \vartheta\tau_R^*, \tau_L = 0, \tau_C \in \mathbb{R}\}$

`REN` a pure renewable energy policy that limits emissions by subsidizing renewable energy; CCS subsidies are zero and the policy space is $\{\tau_R = \vartheta\tau_R^*, \tau_L \in \mathbb{R}, \tau_C = 0\}$

`CCS+REN` a hybrid CCS and renewable energy policy that limits emissions by subsidizing CCS and renewable energy, i.e. $\{\tau_R = \vartheta\tau_R^*, \tau_L \in \mathbb{R}, \tau_C \in \mathbb{R}\}$

The optimal time paths of the policies are calculated for several values of ϑ. We evaluate their mitigation costs with respect to those of the optimal carbon pricing policy ($\vartheta = 100\%$). The mitigation costs of the optimal carbon pricing policy are the welfare losses that arise due to the carbon budget as benefits from emission reductions are neglected. In our standard parametrization mitigation costs are 0.24% (calculated in balanced growth equivalents). The low costs arise because only the electricity sector is considered and mitigation in other sectors is neglected.

The effect of technology policies on welfare and emissions. Fig. 2a shows the performance of the second-best policies compared to the optimal carbon pricing policy. Where data points are missing, no feasible solution was found.[9] The lower ϑ, the higher are the welfare losses of the technology policies

[9]In principle, this may just be a failure of the numerical solver and a solution (although difficult to find) may exist nevertheless. Due to our stepwise reduction of ϑ in 1% intervals and the use of successful solutions as starting point for

because it becomes more and more difficult to reduce emissions at low carbon prices. In particular, for $\vartheta < 50\%$ costs of the renewable or CCS policy more than double, while the compliance costs for the combined policy doubles at $\vartheta = 20\%$. If the carbon price is lower than 13% of the optimal carbon price, the pure CCS policy is even infeasible, due to the imperfect capture rate $\theta = 95\%$. While the pure CCS policy becomes prohibitively expensive or infeasible for low ϑ, a hybrid technology policy achieves the mitigation target at maximum five times the costs of the optimal carbon price policy. This is substantially lower than a pure renewable energy policy (where mitigation costs are more than eight times higher than optimal carbon pricing).

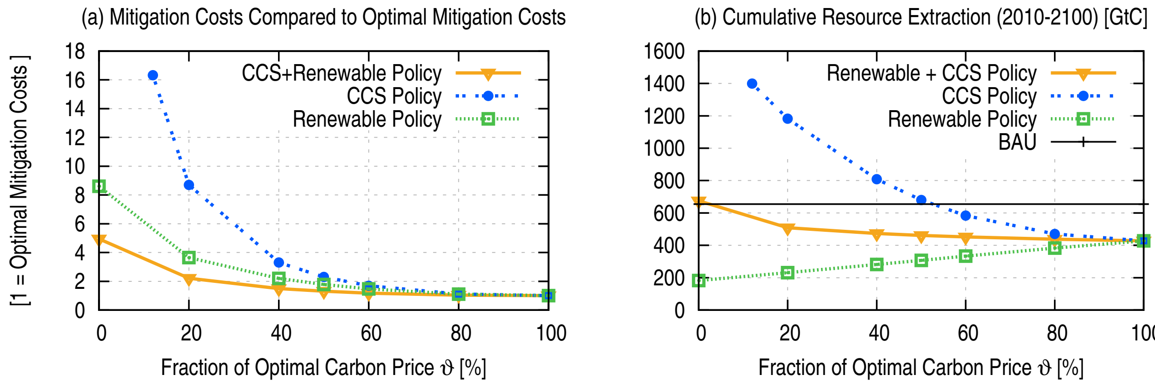

Figure 2: (a) Welfare losses of optimal second-best policies compared to the socially optimal mitigation costs ($\vartheta = 100\%$) under a carbon budget. (b) Impact on cumulative fossil resource extraction within the time span 2010–2100.

While the dynamics in welfare losses are quite similar in the three second-best policy cases, they cause a completely different fossil resource extraction (Fig. 2b): The renewable energy policy increases the relative price of all fossil-resource based technologies compared to the price of renewable energy technologies and therefore reduces fossil resource demand. In contrast, the pure CCS policy induces a relative price advantage for CCS energy compared to conventional fossil and renewable energy. Consequently, CCS is scaled up enormously and fossil resource extraction increases with lower ϑ. If carbon prices fall below 50% of the optimal carbon price, fossil resource extraction exceeds the business-as-usual scenario extraction.

The supply-side dynamics of technology policies. Subsidies on CCS or renewable energy can intuitively be expected to affect the fossil resource price differently: subsidies on CCS increase the demand for fossil resources, raise the scarcity rent, and create an implicit carbon price (for a formal analysis cf. Kalkuhl et al., 2012b). In contrast, when renewable energy are subsidized to become competitive, fossil resource prices are forced downward, dragging the scarcity rent with them.

Showing the components of the resource price, Fig. 3a confirms that this qualitatively carries over to our second-best setting: At the optimal carbon tax ($\vartheta = 100\%$), the tax dominates the net resource price. As the tax is reduced, CCS subsidies cause more extraction. Extraction costs and scarcity rents increase and partially compensate for the decreasing carbon tax. Hence, increasing scarcity rents and extraction costs constitute an implicit carbon price for conventional fossil energy firms. In contrast,

the next calculation, we judge it very unlikely that a feasible solution, particularly one that is similar to the last successful solution, exists.

a pure renewable energy subsidy decreases the scarcity component of the resource price even below the value which results under an optimal carbon price (Fig. 3b). As cheap renewable energy forces the fossil resource price to decrease, increasingly high subsidies are needed to maintain a large price differential between conventional fossil and renewable energy.[10]

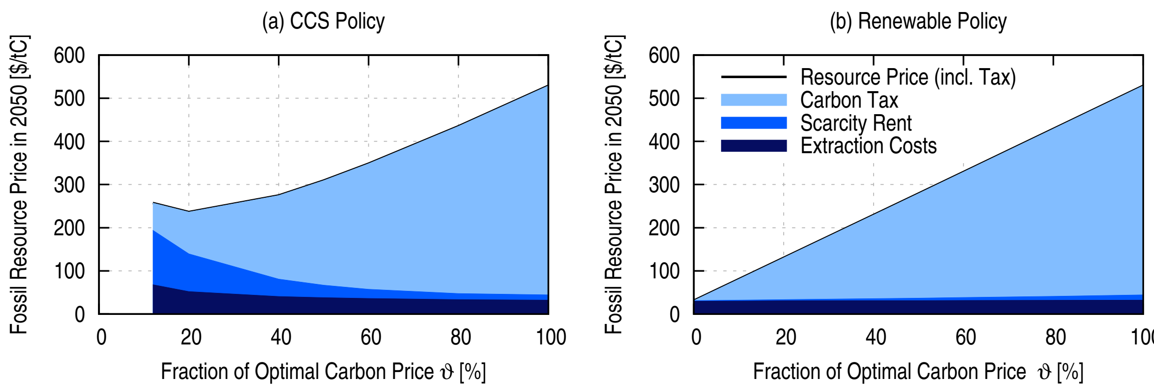

Figure 3: Snapshot of fossil resource prices and their components in 2050 for imperfect carbon prices under (a) a pure CCS policy and (b) a pure renewable energy policy.

The different supply-side dynamics translate directly to the level of the fossil resource rent: As CCS policies increase fossil resource demand, fossil resource rents increase drastically for lower ϑ (Fig. 4a). The introduction of the optimal carbon price reduces fossil resource rents to roughly one fifth compared to the business-as-usual economy. This impact on the fossil resource rent may constitute one important obstacle for implementing a globally harmonized carbon price. However, if carbon taxes are reduced sufficiently and complemented by CCS subsidies, fossil resource rents can even be higher than in the business-as-usual economy. In contrast, the hybrid CCS and renewable energy policy just maintains fossil resource rents at the first best level, and a pure renewable energy subsidy policy even decreases fossil rents further. The reason is that renewable energy subsidies do not only decrease conventional fossil energy deployment but also fossil energy with CCS, implying less fossil resource extraction as in the social optimum (see also Fig. 2b).

With respect to renewable energy generation, Fig. 4b indicates that almost all policies lead to higher renewable energy deployment than in the BAU economy. Except for the pure CCS policy under low carbon prices ($\vartheta < 40\%$), pure CCS policies lead to even higher renewable energy deployment than under an optimal carbon price. The reason is once more the supply-side dynamics: As CCS subsidies increase fossil resource prices they also decrease the relative price of renewable energy compared to fossil energy.

The time-path of technology policies. How do second-best technology policies evolve over time? Fig. 5 shows the trajectory of optimal CCS and renewable energy policies for $\vartheta \in \{0\%, 20\%, 40\%\}$. The second-best CCS subsidies are inverted U-shaped: After an initial increase for several decades, subsidies decline and even turn into taxes in the long run. At this point, renewable energy becomes competitive due to the scarcity of coal; the tax discriminates CCS against renewable energy and this prevents emission leakage from continued CCS usage. Although CCS is taxed in the long-run,

[10]See Kalkuhl et al. (2013) for a detailed discussion of this aspect of renewable energy subsidies.

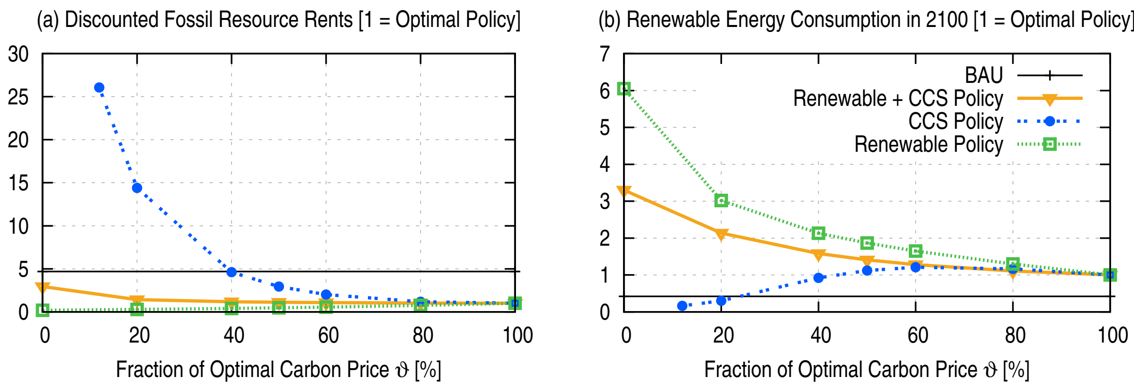

Figure 4: Impact of technology policies on (a) discounted fossil resource rents and (b) renewable energy production in 2100. For the optimal carbon pricing policy, discounted fossil resource rents amount to 0.34% of GDP.

extraction costs and fossil resource prices have become so high due to the early extraction boom that conventional fossil energy generation remains sufficiently low. The taxes on CCS provide now an additional price advantage for renewable energy deployment.

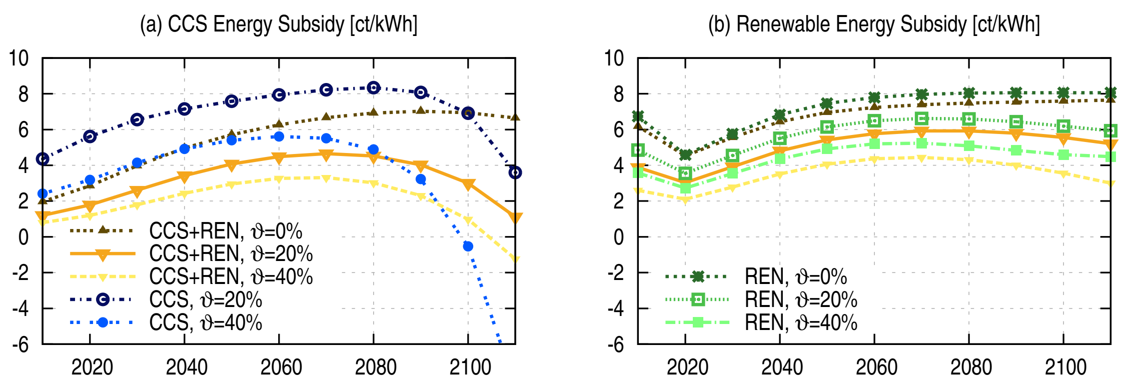

Figure 5: (a) Optimal CCS subsidy and (b) optimal renewable energy subsidy for selected policy scenarios.

In contrast to the CCS subsidies, renewable energy subsidies remain on a more or less stable level. Subsidies drop after an initially high support phase to exploit the learning-by-doing effect but rise again to sustain the competitiveness of renewables. Both figures show that in the hybrid policy case, the subsidy level for each technology is lower than under a pure CCS or renewable energy policy.

Impact on energy prices. Besides reducing fossil resource rents, carbon taxes also increase energy prices and thereby induce further pressure by voters and energy-intensive industries on regulators. Fig. 6 shows how different policies change the energy price relative to the business-as-usual economy. Energy from different technologies are good but imperfect substitutes; we calculate an average energy price by: $\tilde{p}_E = (p_F E_F + (p_L - \tau_L)E_L + (p_C - \tau_C)E_C)/E$. As all second-best policies subsidize energy, they lead to substantially lower energy prices by 2050. Although initially lower, the pure CCS policy leads to higher energy prices in the very long run because fossil resources become more expensive due to their accelerated exploitation.

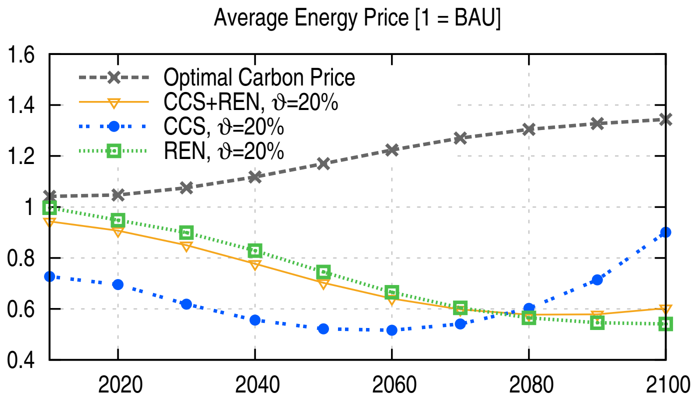

Figure 6: Impact of the optimal carbon prices and second-best policies with 20% of the optimal carbon price on energy prices.

3.2. Second-best policies for delayed carbon pricing

So far we analyzed the capability of technology policies to reduce emissions if carbon prices are permanently low or missing. In this section, we relax this permanence condition and focus on a delayed-carbon pricing scenario.

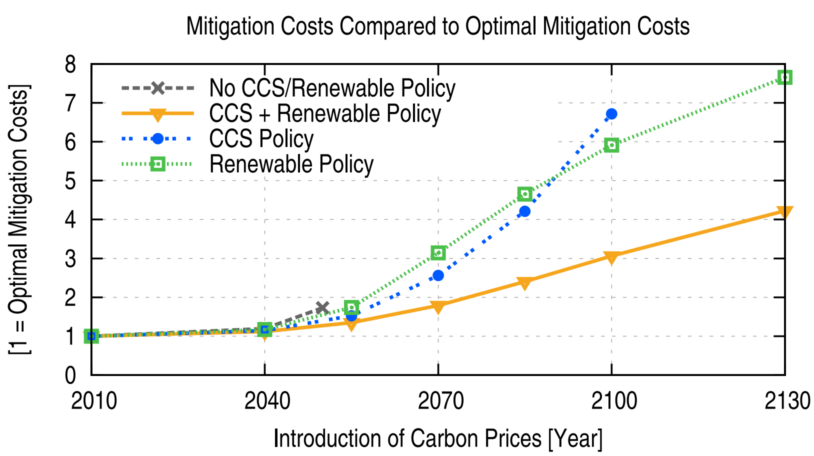

Figure 7: Welfare losses of delayed carbon pricing policies. The right-sided end of trajectories corresponds to the feasibility frontier with respect to delaying carbon pricing. Note that the x-axis denotes the year in which the carbon price is introduced.

For the policy analysis, we set carbon taxes τ_R to zero for $t < T^*$. For $t > T^*$, the government sets an optimal carbon tax.[11] Fig. 7 shows the welfare costs of delaying the introduction of carbon

[11]In this setting, subsidy policies will be instantaneously replaced by the carbon tax at $t = T^*$. When high levels of subsidies have been maintained for decades, the regulator may arguably face some resistance to cutting back subsidies. We

pricing to the year $T^* \in [2010, 2160]$ for several policy scenarios. First, a policy scenario without any technology policies is considered that is only feasible up to a delay until 2050. Without the use of further instruments, delaying the introduction of carbon prices beyond 2050 leads to a violation of the carbon budget. Second, if CCS subsidies are available before the introduction of carbon prices, the critical value of T^* can be postponed until 2100. In this case, mitigation costs are almost seven times higher than for the optimal first-best policy. Third, if renewable energy subsidies are available, the carbon pricing can be delayed arbitrarily. Forth, for a delay until 2100, the ranking of the different policies in terms of welfare costs is similar compared to incomplete carbon pricing – and it should be, as the limiting cases of infinite delay and 100% missing carbon price are actually the same.

However, here renewable energy subsidies only just outperform CCS subsidies, and for smaller delays, they are the more expensive policy. This is because for long time periods of CCS usage, emissions from the CCS sector become substantial (as only 95 percent of emissions can be captured), especially towards the end of the century. Long-term CCS policies need to take this into account and must therefore, much unlike first-best carbon pricing or renewable policies, induce aggressive abatement early on, and incur the high costs associated with this. Contrary, for short-term or medium-term usage of CCS emissions from this sector are not decisive.

Finally, if carbon prices are introduced before 2055, adding renewable energy subsidies to the pure CCS policy brings only small welfare gains. If carbon pricing is introduced much later than 2055, a combination of CCS and renewable energy subsidies is clearly the cheapest second-best policy.

The analysis of delayed policies comes with an important qualification: The considered model framework presupposes a high flexibility between technologies and investments into different technologies. There are no adjustment costs implemented which would increase the costs of switching between technologies in short time intervals. It would further reduce the feasibility frontier for delayed CCS policies. As adjustment costs affect however all technologies, we would not expect a shift in the ranking of the second-best policies.

3.3. Further discussion of incomplete or delayed carbon pricing

Public fund requirements. In the introduction we motivated our investigation of second-best alternatives to carbon pricing by the potential political economy obstacles which the implementation of a price on carbon faces. However, a carbon tax or the auctioning of emission permits *raises* public funds, whereas the technology subsidies discussed here require substantial amounts of public funds. Figure 8 shows the necessary aggregate public expenditures for the incomplete carbon price scenarios (Section 3.1) and delayed carbon pricing (Section 3.2). In our model these funds are raised through a non-distortionary poll tax; hence even large public expenditures pose no problem. However, if this idealized assumption was relaxed, then revenue raising taxation would distort the economy, and depending on the specific tax, the additional cost of public funds could be substantial. Welfare losses of the second-best policies would be exacerbated, if this was taken into account. Carbon pricing, in contrast, alleviates an externality, thus reducing distortion of the economy (though the climate externality is not modeled here).

Economic growth and the transformation of the energy system. In the supplementary material we present further figures showing the development of key economic variables for different policies.

have explored this by limiting the subsidy phase-out to 4% per year. Since the difference in results was negligible, we only show results without such constraints.

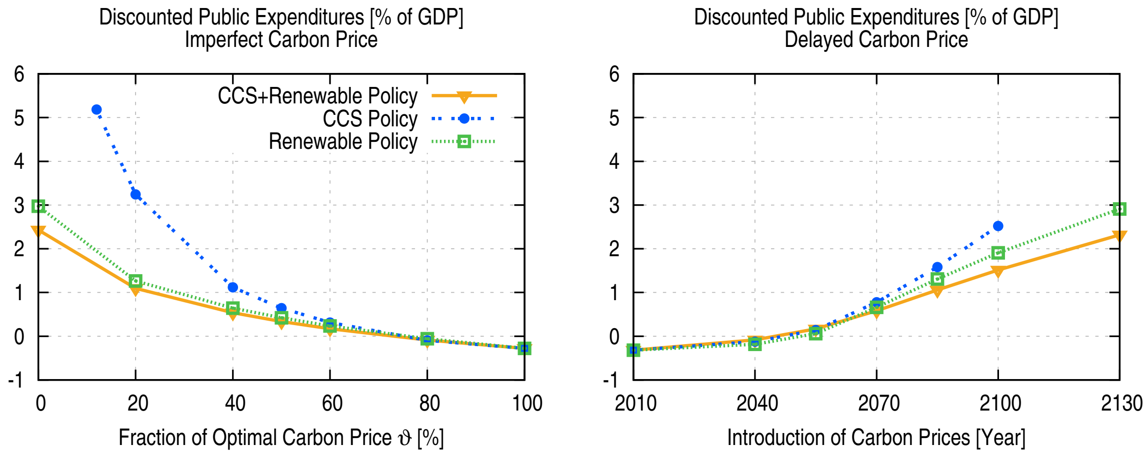

Figure 8: Aggregate public expenditure for (a) incomplete and (b) delayed carbon pricing

Here, we summarize the most important insights. CCS policies – either in the imperfect carbon or in the delayed carbon price setting – tend to reduce short-term consumption drastically while having a less negative impact (or even a small positive impact) on mid-term consumption. Economic output (GDP) increases for all technology policies up to 1.5% compared to the business-as-usual scenario because lower energy prices boost production and fossil resource use (in case of CCS subsidies). Simultaneously, wages increase under subsidy policies due to lower energy prices and higher production. The higher economic growth and increased wages, however, do not translate into higher consumption due to the large tax burden to finance technology policies. The political feasibility of technology subsidies depends therefore crucially on the distribution of the tax burden in the society.

Regarding the time-path of emission reductions, CCS policies induce a flatter emission reduction path, implying lower emissions from the first period and less steep reductions. For the CCS policy with $\vartheta = 20\%$ of the optimal carbon price, emissions peak only at the end of this century. Renewable energy policies, in contrast, lead to higher emission levels in the first period and strong subsequent declines. While both dynamics are compatible with the given carbon budget, they might imply different temperature levels – at least in the medium-run. Meinshausen et al. (2009) suggest that temperature changes can be well proxied by cumulative emissions neglecting the temporal dynamics. Calculations of the resulting temperature levels with MAGICC 6 (Meinshausen et al., 2011) indicate that the temperature level of the renewable policy with steep reductions but higher initial emissions leads to a 9% higher temperature level in 2100 than the CCS policy with flat reductions.[12] These low variations in temperature levels might be tolerable as they also tend to diminish for longer time horizons.

The transformation of the energy system is also affected by the policy: CCS policies lead to a strong up-scaling of CCS peaking at the second half of the century. After the peak (which is also traced by the peak in coal extraction), renewable energy starts to replace fossil CCS energy. Contrary, renewable energy policies lead to strong and permanently growing renewable energy production while fossil energy (with or without CCS) is relegated to a niche existence.

[12]The implementation we used is the freely available liveMAGICC at http://live.magicc.org. We focused on the renewable policy and the CCS policy under imperfect carbon pricing with $\vartheta = 20\%$ as the time profile of these two policies differ most.

4. Sensitivity analysis

In this section we provide two different types of sensitivity analyses. The first one focuses on how different structural parameters of the economy influence the mitigation costs of several policy instruments that achieve the carbon budget. The second set of sensitivity analyses considers the environmental effectiveness of different policies if they deviate from their optimal values. The source of uncertainty in this case can be attributed to the imperfect understanding of structural parameters (that leads to 'wrong' policies) or in the imperfect political implementation process despite perfect knowledge of the structural parameters.

4.1. Costs of policies

Fossil resource size, extraction costs and renewable energy costs. The size of exploitable fossil resources S_0 in the ground is very uncertain: BGR (2010) quantifies the size of proven oil, gas and coal reserves with 856 GtC (both, conventional and unconventional). There are further 2,064 GtC oil and gas and 12,417 GtC coal resources estimated where technical feasibility, extraction costs and the magnitude of extractable carbon is speculative.

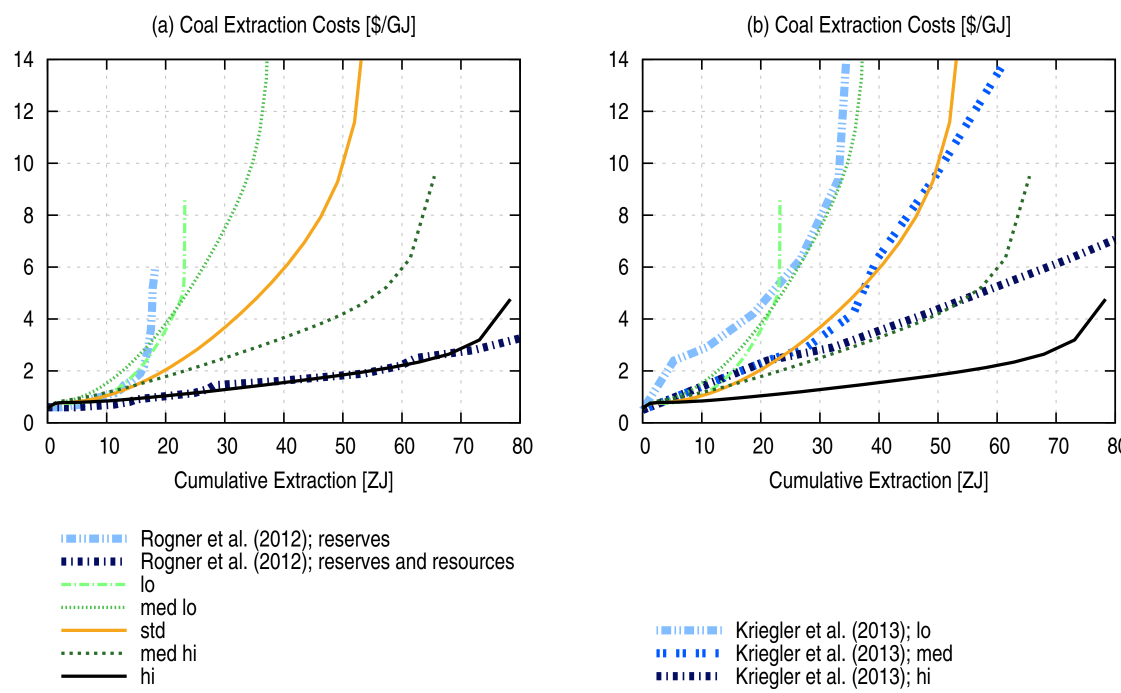

Figure 9: Extraction costs curves under parameter variations in Table 1 and in comparison to (a) Rogner et al. (2012) and (b) Kriegler et al. (2013).

We therefore base our extraction cost scenarios on estimated cost curves from two sources: Rogner et al. (2012) who provide the most recent and comprehensive assessment of fossil resources and extraction costs, and Kriegler et al. (2013) who use different extraction cost scenarios based on expert interviews for an international model comparison project. In Fig. 9a we depict the extraction cost curve based on known and proven coal reserves from Rogner et al. (2012) and calculate coal 'reserves and resource' extraction cost curve based on the cost and availability estimates of coal resources given in Rogner et al. (2012). While the reserves-based curve provides a confident upper bound of the cost curve, the resource-based curve is a highly uncertain estimate of the lower bound. Fig. 9b – based on expert interviews in Kriegler et al. (2013) – shows a narrower range of cost curves. Our standard parametrization corresponds to the medium scenario in Kriegler et al. (2013). For our sensitivity analysis we use four further parametrizations of extraction cost curves which are close to the different estimates of Rogner et al. (2012) and Kriegler et al. (2013) (see Fig. 9). The parameters of the different extraction cost curves can be found in the upper panel of Table 1.

With respect to the resource base S_0 (Tab. 1), our calculations suggest a somewhat paradoxical conclusion: When (cheap) fossil resources are scarce (i.e. the 'low' column in Tab. 1), subsidizing CCS is always cheaper than subsidizing renewable energy only. This even holds for the case of very low renewable energy costs (lower panel of Tab. 1). In the case of low fossil resource availability, the pure CCS subsidy is only 22% more expensive than the optimal carbon pricing policy. The explanation for this outcome is again rooted in the supply-side dynamics: A pure renewable energy subsidy has to be very high in order to reduce fossil resource extraction. In contrast, a moderate CCS subsidy does not only encourage the capturing of carbon emissions, it also encourages fossil resource exploitation. This accelerated depletion increases extraction costs and scarcity rents, making renewable energy attractive without renewable energy subsidies. Hence, a CCS policy can be a cheaper way to accelerate the energy transition to renewable energy, if fossil resources are sufficiently scarce. This is the case if only a fraction of the assumed coal resources can be exploited technically and economically. The comparative cost advantage of the CCS policy over the renewable energy subsidy diminishes for the 'standard' or 'high' resource availability scenarios. If renewable energy becomes sufficiently cheap, renewable energy subsidies outperform the CCS subsidy in the delayed policy scenarios already for 'medium-low' resource availability (lower panel of Tab. 1).

Further structural parameters. Uncertainties exist also with respect to other parameters: CCS is still a relatively new technology with little experience, and therefore capture rates θ, leakage rates δ_X, underground storage capacity X_0 and overall costs (captured by the technology level parameter A_C) are uncertain. The substitutability σ_3 between the three generic energy technologies is also difficult to measure directly and might change with further innovations and the invention of new technologies. Furthermore, the stringency of the mitigation target B_0 is difficult to predict because there are scientific uncertainties regarding the climate system and the magnitude of climate damages as well as political uncertainties regarding the international negotiations for a harmonized mitigation policy. Variation of the parameters θ, δ_X, X_0, σ_3, B_0 and A_C are shown in Tab. C.3 in AppendixC. As the pure CCS policy is already infeasible in our standard parameter setting, we also consider a delayed carbon pricing policy with $T^* = 2070$. Hence, we compare the CCS policy (CCS_60) with the renewable energy policy (REN_60) if carbon pricing is delayed by six decades.

Before discussing the relative performance of instruments, we examine the mere feasibility of CCS policies for achieving the mitigation target. The sensitivity analysis indicates that pure long-term CCS policies are feasible if the capture rate θ is sufficiently high, the carbon budget B_0 not too ambitious or fossil resources sufficiently scarce (Tab. 1 and Tab. C.3). The temporary CCS policy is always feasible except for the case of high leakage rates. In contrast to CCS policies, renewable energy policies are always feasible.

Regarding the costs of second-best policies, we find that CCS policies in the delayed carbon pricing scenarios – where feasible – are in many cases cheaper than renewable energy policies. There are, however, also conditions where the temporary renewable energy subsidy is cheaper than the

Table 1: Mitigation costs (for optimal mitigation) and additional second-best costs (for all other scenarios, relative to optimal mitigation costs) for different extraction cost curves

Resource base	low	medium-low	standard*	medium-high	high
Parameters					
Resource base S_0 [GtC]	600	1,000	4,000	6,000	12,000
Scaling parameter χ_2	40	100	700	230	200
Slope of cost cost curve χ_3	3	2	2	1.3	1.3
Normal renewable energy costs (9 ct/kWh after learning; $A_{L,max}$ = 0.60)					
Optimal mitigation costs [% BGE]	0.157	0.204	0.242	0.253	0.279
Pure CCS subsidy (CCS) [1=optimal mitigation costs]	1.23	1.52			
Pure renewable subsidy (REN)	12.83	9.54	8.60	8.00	7.69
Portfolio policy (CCS+REN)	1.23	1.52	4.95	4.97	5.12
CCS subsidy with ϑ = 40%	1.13	2.96	3.30	3.46	3.71
Renewable subsidy with ϑ = 40%	2.95	2.30	2.20	2.11	2.08
Portfolio subsidy with ϑ = 40%	1.13	1.49	1.49	1.47	1.47
CCS subsidy + delayed carbon price (CCS_60)	1.22	2.42	2.56	2.49	2.63
Renewable subsidy + delayed carbon price (REN_60)	4.32	3.22	3.14	2.92	2.95
Portfolio + delayed carbon price (CCS_60+REN_60)	1.21	1.74	1.79	1.73	1.78
Low renewable energy costs (6 ct/kWh after learning; $A_{L,max}$ = 0.85)					
Optimal mitigation costs [% BGE]	0.084	0.092	0.109	0.112	0.126
Pure CCS subsidy (CCS) [1=optimal mitigation costs]	1.30	1.88			
Pure renewable subsidy (REN)	9.81	8.39	7.65	7.21	6.88
Portfolio policy (CCS+REN)	1.30	1.88	5.32	5.22	5.24
CCS subsidy with ϑ = 40%	1.21	6.00	7.28	8.52	9.55
Renewable subsidy with ϑ = 40%	2.45	2.25	2.08	2.02	1.94
Portfolio subsidy with ϑ = 40%	1.21	1.66	1.60	1.58	1.54
CCS subsidy + delayed carbon price (CCS_60)	1.28	2.52	4.67	2.64	2.90
Renewable subsidy + delayed carbon price (REN_60)	2.45	2.07	2.10	1.97	2.02
Portfolio + delayed carbon price (CCS_60+REN_60)	1.28	1.56	1.60	1.54	1.58

Note. Mitigation costs denote welfare losses (in balanced growth equivalents) of the optimal carbon pricing policy relative to the BAU scenario; second-best costs are mitigation costs relative to the optimal mitigation costs. The asterisk is assigned to the value used for the standard parametrization. Blank entries denote infeasibilities, i.e. the policy instrument cannot achieve the mitigation target. CCS_60 denotes the CCS policy if carbon pricing is delayed by 60 years; REN_60 the corresponding renewable energy policy.

temporary CCS subsidy: a high leakage rate (0.1%), a very low storage capacity (200 GtC), a tight carbon budget ($< 100GtC$), or very high CCS costs (4.2 ct/kWh price difference to conventional fossil energy). Complementing the pure renewable energy subsidy by a CCS policy leads always to substantial welfare gains, except when leakage rates are very high. Finally, while the pure renewable energy policy is fairly insensitive to the capture rate and the underground storage capacity, CCS policies perform best for high capture rates, low leakage rates and a high storage capacity.

Fig. 10a addresses the fossil resource rents as an indicator for political feasibility. It shows that temporary CCS policies can diminish rent losses by increasing total mitigation costs by a factor of two or three. However, a pure CCS policy – if feasible – overcompensates fossil resource owners by increasing rents by a multitude (data points beyond the range of Fig. 10a). In contrast, most

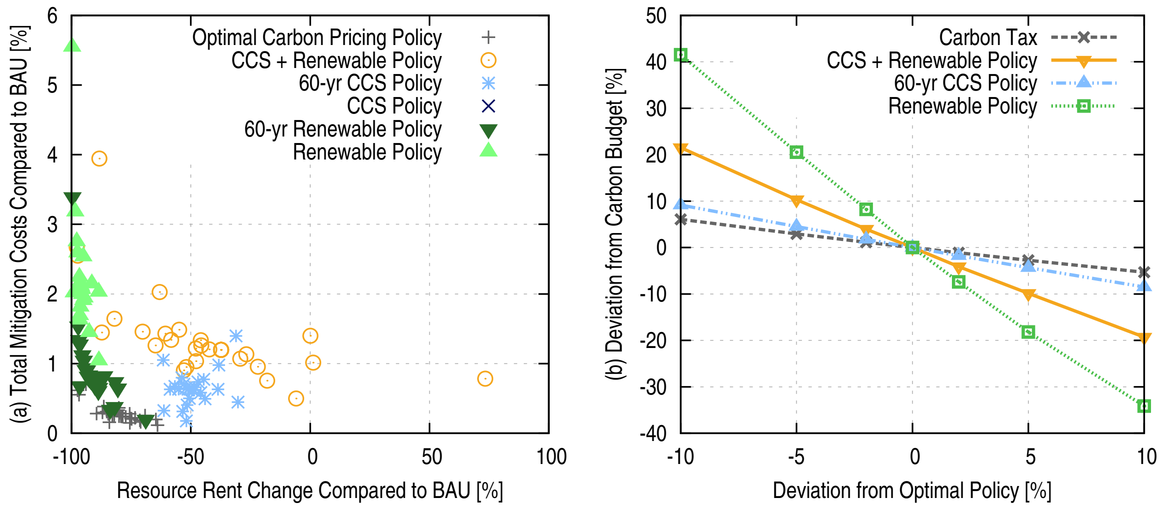

Figure 10: (a) Correlation between resource rent change and mitigation costs (welfare losses [% BGE] compared to BAU) under all parameter variations shown in Tab. 1 and Tab. C.3. The data points for the pure CCS subsidy policy are excluded as they lie far outside the other data points (rent increases by several hundred percent). (b) Change in emissions if the policy instrument is changed around its optimal value. As the pure CCS subsidy is not feasible under the standard parametrization, we used the CCS subsidy under a delayed carbon pricing policy (60 years delay).

renewable energy policies decrease fossil resource rents below the optimal carbon pricing policy. If not complemented by CCS subsidies, welfare losses are quite high.

4.2. Environmental effectiveness

So far we studied how different parameter changes influence the performance of policies. In the following, we focus on the sensitivity of policy instruments with respect to emission reductions and welfare. Policy-makers do not have perfect information about all economic parameters and technologies and the political implementation process is an outcome of a complex interplay of interests. Thus, taxes or subsidies will likely deviate from the optimal value.

For Fig. 10b, we first increase and decrease each of the labeled policy instrument by 2, 5 and 10 percent (in each time step) compared to the respective optimal value. We then implement these policies in the laissez-faire economy and display the change in cumulative emissions. As intuition suggests, lower carbon taxes and lower subsidies for low-carbon technologies lead to higher emissions. Cumulative emissions react highly sensitive to a pure renewable energy policy: If subsidies are only 2 percent lower than their optimal value, carbon emissions increase by 8 percent. In contrast to renewable energy policies, the sensitivity of carbon pricing and CCS policies is very low and hardly distinguishable. The high sensitivity for renewable energy subsidies results from the learning-by-doing dynamics: if subsidies are too low, learning-by-doing is slowed down, which leads to additional cost increases for renewable energy (and *vice versa* if subsidies are too high). Hence, the impact on the energy mix is amplified in both directions.

Fig. 10b indicates that the quantitative effect of suboptimal carbon taxes on emissions is low. As argued by Sinn (2008), suboptimal carbon taxes can accelerate emissions and, thus, global warming. While we confirm that lower carbon prices lead to higher emissions, the response is rather inelastic: A 10 percent decrease of carbon taxes leads only to a 6 percent increase in cumulative emissions.

5. Conclusions

It is questionable whether the governments of all nations will agree on a substantial global price on carbon in the next decades. As a response to this global policy failure, second-best technology policies for reducing carbon emissions become an important alternative. Our model analysis suggests that medium-term policies promoting carbon capture and storage could play a key role for transforming the energy system. Due to the supply-side dynamics of fossil resource extraction, subsidies for CCS can accelerate the transformation to a carbon-free economy at lower cost than renewable energy policies – assuming favorable geological and technical conditions. As CCS subsidies increase the demand for fossil resources they lead to higher fossil resource prices. Thus, an implicit price on carbon is created that co-benefits renewable energy deployment. As a result, renewable energy deployment can be even higher than under an (efficient) first best carbon pricing policy. In contrast, a pure renewable energy policy decreases fossil resource prices by reducing the demand. Consequently, they act as an implicit small subsidy on carbon, making high renewable energy subsidies necessary to crowd out fossil energy.

An at first glance paradoxical conclusion is that the comparative cost advantage of CCS policies over renewable energy policies is greater the scarcer fossil resources are. Although the future belongs to the 'renewables' and renewable energy might be a cheaper *technology* than CCS, a temporary CCS subsidy could be the cheaper *policy* to transform the energy sector when carbon prices are missing. The second-best costs of CCS policies are the lower (i) the better carbon can be captured in power plants, (ii) the lower carbon leakage is, and (iii) the larger the underground storage capacity is. If, in contrast, fossil resources are abundant and renewable energy costs low or if carbon taxes are permanently on suboptimally low levels (rather than delayed), renewable energy subsidies can outperform CCS subsidies.

While renewable energy policies are always a feasible (but sometimes more expensive) second-best policy in case of missing carbon prices, CCS policies cannot always guarantee to achieve ambitious mitigation targets: underground storage capacity, capture rates and the politically targeted carbon budget have to be sufficiently high and carbon leakage sufficiently low. If the introduction of carbon taxes is delayed, CCS subsidies can replace carbon pricing for a certain time span, but become more difficult and even infeasible for very long time horizons. CCS policies are therefore an attractive medium-term option to buy time until the international community agrees on a carbon price. Due to the feasibility constraints, a long-term CCS policy, however, may also be a risky policy.

CCS and renewable energy subsidies differ in their impact on fossil resource rents: As CCS policies increase fossil resource extraction and, thus, fossil resource prices, they lead to higher energy prices in the long run. In contrast, renewable energy subsidies decrease energy prices substantially below the business-as-usual price. This benefits energy-intensive industries and possibly also low-income-households, which could increase the political support for this policy. Technology subsidies further increase wages although the tax burden to finance subsidies outweighs the positive wage effect for a representative household. Political feasibility depends therefore crucially on the distribution of the tax burden in the society. With respect to fossil resource rents, CCS policies mitigate the rent losses associated with climate policy and can even over-compensate fossil resource owners at moderate additional costs.

Although there is no global government to implement these policies, international negotiations about emission reductions could use these insights when focusing on technology protocols and technology financing mechanisms. The cost mark-ups for CCS in developing countries could be paid by OECD countries. This establishes a no-regret option for developing countries, allowing them to extend their energy system in an almost business-as-usual way without substantial additional costs. If a critical mass of countries adopts CCS policies, the increasing fossil resource prices could also lead to lower emissions in countries not participating.

There are, of course, several limitations of our model that raise further important questions. First, increasing fossil resource prices due to CCS policies could increase exploration activities leading *ceteris paribus* to lower scarcity rent increases. This effect could be integrated in a modified formulation of the extraction cost curve (by including exploration costs) and the initial resource base (by including estimations about fossil resources). We paid tribute to this consideration in our sensitivity analysis by varying the resource base and the extraction costs. Fossil resource price increases might also have adverse effects on deforestation and food prices due to the expansion of energy crop cultivation. Second, (temporary) CCS policies conserve or even strengthen the existing fossil-fuel based industrial metabolism. While this eases political implementation in the short-term, it could impede the delayed transformation to renewable energy. In particular, if fossil resources turn out not to be scarce (and the implicit carbon tax effect of CCS subsidies is small), there is low economic pressure to invest into renewable energy. As underground carbon storage fills up and fossil resource prices are continuously low, additional political measures are necessary to decarbonize the energy system. However, when large investments into fossil capital have already been undertaken, introducing carbon prices or renewable energy subsidies might become even more difficult. Finally, there has to be a proper management of CCS storage sites, including an effective monitoring system which detects leakage as well as an appropriate design regarding the long-term liability for leakage and the sharing of environmental risks between firms and the public (Held and Edenhofer, 2009; IPCC, 2005). Underground storage is a further scarce exhaustible resource requiring well-defined and secure property rights for an efficient intertemporal allocation. This could, in particular, become crucial if scarce storage has to be used for capturing emissions from combustion of biomass. As this technology can create negative net emissions, the remaining storage capacity might become highly valuable in the future. If there are no auctions or fees for use concessions of underground storage, this scarcity rent is transferred implicitly to CCS operators.

Beside these limitations, our findings suggest an important conclusion: Pure CCS as well as pure renewable energy policies aiming to replace a permanently missing carbon price are not a pragmatic policy approach. Both, CCS and renewable energy policies carry specific risks of failure: CCS policies rely on favorable physical and technological conditions; renewable energy policies are costly and lead to a highly sensitive emissions outcome that undermines environmental effectiveness. A smart combination of both policies, however, might be a robust second-best strategy. Such a hybrid policy would initially push CCS to increase fossil resource prices in a sustained way. With ongoing depletion, extraction costs and scarcity rents increase. This makes lower CCS subsidies necessary and even turns the optimal CCS subsidy into a tax in the long run. As fossil resource prices continue to increase, renewable energy – permanently backed by moderate subsidies – becomes more and more the dominant low-carbon technology. The second-best-costs of this hybrid policy approach and its risks decrease further in case carbon pricing can be eventually introduced in the future.

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AppendixA. First-order conditions of the CCS sector

Maximizing the associated Lagrangian with λ_X as co-state variable for X, we obtain as dynamic first-order conditions:

$$\lambda_{X,t} = p_{X,t} - h(X_t) \tag{A.1}$$

$$\lambda_{X,t-1}(1 + (r_t - \delta)) - \lambda_{X,t} = -\left(\frac{\partial h(X_t)}{\partial X_t} R_{X,t} + \delta_X \tau_R\right) \tag{A.2}$$

$$\lambda_{X,t} X_{t+1} = 0 \tag{A.3}$$

AppendixB. Parameters

Population L grows exogenously from L_0 to L_{max} according to $L_t = L_0(1 - q_t) + q_t L^{max}$ with $q_t = 1 - \exp(-ft)$. Labor productivity A_Y grows exogenously at the variable rate $[1 - g_0 \exp(-\zeta t)]^{-1} - 1$ implying for $g_0 = 0.026$ and $\zeta = 0.006$ an initial growth rate of 2.7% which decreases to 1.5% in 2100.

Table B.2: Parameters used for the numerical model

Symbol	Parameter	Value
ρ	pure time preference rate of household	0.03
η	elasticity of intertemporal substitution	1
δ	capital depreciation rate	0.03
L_{max}	population maximum (bill. people)	9.5
f	population growth parameter	0.04
a_1	share parameter in final good production	0.96
σ_1	elasticity of substitution energy–intermediate	0.5
b_2	share parameter in intermediate production	0.7
σ_2	elasticity of substitution labor–capital	0.7
a_3, b_3, c_3	share parameter (energy usage)	1
σ_3	elasticity of substitution energy types	3
a_F	share parameter in fossil energy generation	0.8
A_C	productivity factor conventional fossil energy	2.7
σ	elasticity of substitution fuel–capital	0.15
a_C	share parameter in fossil energy generation	0.95
A_C	productivity factor CCS energy	2.2
θ	capture rate	0.95
χ_1	scaling parameter	5
χ_2	scaling parameter	700
χ_3	slope of extraction curve	2
c_1	scaling parameter (10^4\$/tC)	0.05
c_2	scaling parameter (10^4\$/tC)	0.45
c_3	slope of storage and transportation cost curve	2
δ_X	leakage rate	10^{-4}

Continued ...

Table B.2: (continued)

Symbol	Parameter	Value
ν	share parameter learning carbon-free energy generation	0.95
$A_{L,max}$	maximum productivity learning carbon-free energy	3.4
Ω	scaling parameter	200
γ	learning exponent	0.27
Q	land	1
K_0	Initial total capital stock (trill. US$)	165
S_0	Initial stock of fossil resources (GtC)	4000
S_0	Underground carbon storage capacity (GtC)	3500
B_0	Carbon budget (GtC)	150
H_0	Initial experience stock renewable energy	0.2
L_0	Initial population (bill. people)	6.5
$A_{Y,0}$	Initial productivity level	6
T	time horizon (in years)	150

AppendixC. Sensitivity analysis

Table C.3: Mitigation costs (in BGEs) and additional second-best costs (relative to optimal mitigation costs) for several policies

Capture rate θ	0.91	0.93	0.95*	0.97	0.99
Optimal mitigation costs [% BGE]	0.28	0.26	0.24	0.22	0.2
2nd-best costs (CCS+REN) [1=optimal mitigation costs]	5.25	5.14	4.95	4.59	3.98
2nd-best costs (CCS_60)	2.87	2.7	2.56	2.86	2.28
2nd-best costs (REN_60)	2.94	3.03	3.14	3.25	3.29
2nd-best costs (CCS)				18.88	7.49
2nd-best costs (REN)	7.6	8.04	8.6	9.35	10.69
Leakage rate [%] δ_X	0	0.01*	0.1	1	2
Optimal mitigation costs [% BGE]	0.24	0.24	0.3	0.55	0.62
2nd-best costs (CCS+REN)	4.82	4.95	5.51	4.61	4.33
2nd-best costs (CCS_60)	2.48	2.56	3.52		
2nd-best costs (REN_60)	3.12	3.14	3.06	2.31	2.18
2nd-best costs (CCS)					
2nd-best costs (REN)	8.8	8.6	7.23	4.68	4.46
Elasticity of Substitution σ_3	2	3*	4	5	6
Optimal mitigation costs [% BGE]	0.15	0.24	0.29	0.33	0.36
2nd-best costs (CCS+REN)	9.45	4.95	3.54	2.87	2.47
2nd-best costs (CCS_60)	2.2	2.56	2.27	1.95	1.73
2nd-best costs (REN_60)	2.31	3.14	3.22	3.16	3.08
2nd-best costs (CCS)					
2nd-best costs (REN)	17.12	8.6	6.22	5.11	4.46
Storage Capacity X_0 [GtC]	200	500	1000	1500	3500*
Optimal mitigation costs [% BGE]	0.28	0.25	0.24	0.24	0.24
2nd-best costs (CCS+REN)	5.12	5.00	4.96	4.95	4.95
2nd-best costs (CCS_60)	26.68	2.67	2.59	2.57	2.56
2nd-best costs (REN_60)	2.72	3.02	3.11	3.13	3.14
2nd-best costs (CCS)					
2nd-best costs (REN)	7.32	8.23	8.49	8.56	8.60

Continued ...

Table C.3: (continued)

Carbon Budget B_0 [GtC]	50	100	150*	200	250
Optimal mitigation costs [% BGE]	0.70	0.38	0.24	0.16	0.11
2nd-best costs (CCS+REN)	5.61	5.28	4.95	4.62	4.34
2nd-best costs (CCS_60)	23.79	3.64	2.56	1.91	1.53
2nd-best costs (REN_60)	4.83	4.01	3.14	2.32	1.71
2nd-best costs (CCS)					15.83
2nd-best costs (REN)	7.89	8.29	8.60	8.86	9.07
CCS costs A_C	2.6	2.4	2.2*	2.0	1.8
Difference to fossil energy w/o CCS [ct/kWh]	0.6	1.3	2.0	3.0	4.2
Optimal mitigation costs [% BGE]	0.19	0.21	0.24	0.27	0.31
2nd-best costs (CCS+REN)	5.16	5.04	4.95	4.86	4.79
2nd-best costs (CCS_60)	2.19	2.36	2.56	2.82	3.15
2nd-best costs (REN_60)	3.29	3.23	3.14	3.04	2.92
2nd-best costs (CCS)					
2nd-best costs (REN)	10.29	9.41	8.6	7.87	7.22

Note. Mitigation costs denote welfare losses in balanced-growth equivalents of the optimal carbon pricing policy relative to the BAU scenario; additional second-best costs refer to the mitigation costs relative to the optimal carbon pricing policy. The asterisk is assigned to the value used for the standard parameterization. Blank entries denote infeasibilities, i.e. the policy instrument cannot achieve the mitigation target. CCS_60 denotes the CCS policy if carbon pricing is delayed by 60 years; REN_60 the corresponding renewable energy policy, if carbon pricing is introduced in 2070.

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